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Transforming dust to planets

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Abstract We review recent progress in understanding how nebular dust and gas are converted into the planets of the present-day solar system, focusing particularly on the "Grand Tack" and pebble accretion scenarios. The Grand Tack can explain the observed division of the solar system into two different isotopic "flavours", which are found in both differentiated and undifferentiated meteorites. The isotopic chronology inferred for the development of these two "flavours" is consistent with expectations of gas-giant growth and nebular gas loss timescales. The Grand Tack naturally makes a small Mars and a depleted, dynamically-excited and compositionally mixed asteroid belt (as observed); it builds both Mars and the Earth rapidly, which is consistent with the isotopically-inferred growth timescale of the former, but not the latter. Pebble accretion can explain the rapid required growth of Jupiter and Saturn, and the number of Kuiper Belt binaries, but requires specific assumptions to explain the relatively protracted growth timescale of Earth. Pure pebble accretion cannot explain the mixing observed in the asteroid belt, the fast proto-Earth spin rate, or the tilt of Uranus. No current observation requires pebble accretion to have operated in the inner solar system, but the thermal and compositional consequences of pebble accretion have yet to be explored in detail.

Keywords Accretion, isotope cosmochemistry, orbital migration, planetary interiors

1. Introduction

The present-day characteristics of our solar system - and other planetary systems - are largely controlled by the processes which transformed the original dust and gas of the solar nebula into planets. These processes, however, are still imperfectly understood; for instance, simultaneously explaining the characteristics of the inner rocky planets and the outer gas giants is proving to be very challenging. In this chapter, we review our current understanding of the processes of planet growth, focusing mainly on our own solar system.

We begin by outlining some of the key questions we would like to answer. In Section 2, we provide a brief overview of the observational constraints, both physical and chemical, which any successful formation scenario must match. We then go on to discuss our current understanding of planetary growth processes, and divide this discussion into two halves. The first half discusses "early" accretion, assuming that nebular gas plays an important role. The second half discusses "late" accretion, covering growth to full-size planets, in which the presence of gas may or may not be important. As will be seen below, the timing of when the gas is lost relative to other events is a critical factor in determining the final solar system architecture. We conclude with a summary which focuses on the key unanswered questions, and how they may be resolved in future.

In the last decade, arguably the most important theoretical advances have been the recognition of the role of gas giant migration, and (more recently) the potentially important process of "pebble accretion". At the same time, isotopic measurements of solar system solids have clarified both the timescales and locations of various important processes. Despite these rapid advances, several recent reviews are available which cover a similar set of topics. In particular, those by Youdin & Kenyon (2013), Chambers (2014), Jacobson & Walsh (2015), Nimmo & Kleine (2015) and Morbidelli & Raymond (2016) treat particular aspects in more detail than we can do here.

1.1 Key questions

There are a few commonly-used names for building blocks of planets, mainly depending on their sizes. In order of increasing sizes, these are dust particles (~microns), pebbles (mm-10cm), planetesimals (~10-100 km), and planetary embryos (> 1000 km). The distinction between the first pair and the second pair is due to their different responses to nebular gas (Section 3.1.2); the distinction between planetesimals and embryos is a consequence of how accretion proceeds (Section 3.2.1). These are only guidelines, and there are overlaps in sizes between different categories. We will highlight a few important questions regarding different growth stages of planets here, and discuss potential solutions in Section 3.

1.1.1 How did growth proceed beyond meter-scale objects?

The initial stage of solid body growth proceeds as dust grains collide with one another. This pairwise growth is expected to stall for cm-sized particles, because bouncing and fragmentation become more important with increasing size (e.g., Blum & Wurm 2008, Brauer et al. 2008, Windmark et al. 2012, and Birnstiel et al. 2012; see Section 3.1.1 for details). These pebble-sized particles start decoupling from the gas and their evolution is controlled by gas drag. The resulting rapid migration of these pebbles hinders the further growth of bodies and thus is called the "meter-size" barrier (Adachi et al. 1976, Weidenschilling 1977). The rapid migration occurs due to the difference in orbital speeds of a gas disk and solid particles; since the gas generally rotates at sub-Keplerian velocities due to pressure support, the solid particles feel a headwind, lose angular momentum, and migrate inward. The radial speed of this migration is the fastest for roughly m-sized objects (about 100 yrs at 1 AU, Adachi et al. 1976, Weidenschilling 1977) for typical disk parameters. Possible solutions to the difficulty in growing beyond m-sized objects are discussed in Section 3.1.2. Once the bodies reach about 10 km in size, they fully decouple from the gas and are called "planetesimals". In the presence of the pebble flux, large enough planetesimals are expected to grow rapidly to planetary embryos or to planets (see Section 3.1.2.).

1.1.2 How did gas giant cores grow rapidly in the outer but not inner solar system?

The mass distribution of planets in the solar system changes drastically between Mars and Jupiter. The inner planets are low-mass and rocky, while the outer planets are more massive and less dense due to large gas envelopes. The difference has been explained by the existence of a "snow line" between Mars and Jupiter orbits. Beyond the snow line, water molecules condense and about twice as much solid material is available to form more massive planetary cores (Lodders 2003). Rapid gas accretion occurs for ~10 Earth-mass (M_E) cores, when the gas envelope can no longer be in the hydrostatic equilibrium (e.g. Bodenheimer & Pollack 1986). The fact that Jupiter and Saturn have large envelopes implies that massive cores were formed before the solar nebula dissipated. However, in classical accretion models the time required to build a 10 M_E core is too long compared to a typical gas disk's lifetime of ~3 Myr; and this problem applies equally to distant gas giants found in other solar systems (Section 3.1.3). One possible solution is to assume a more massive protostellar disk than the Minimum-mass Solar Nebula (e.g., Thommes et al. 2003). So-called pebble accretion, however, may be able to form cores very quickly compared to the classical model (e.g., Lambrechts & Johansen

2012, also see Section 3.1.2). Whether this scenario can be reconciled with the absence of gas giants in the inner solar system is an open question.

1.1.3 Why is Mars small?

Early accretion models assumed that the final stage of terrestrial planet formation in the solar system takes place in the presence of giant planets which have their current masses and orbital parameters (e.g. Agnor et al. 1999, Chambers 2001). These models successfully reproduced many inner solar system features, including inferred formation timescales (less than 200 Myr), the number of planets (typically 3-4), and the radial distribution of mass. However, it proved hard to produce planets with masses as small as Mercury and, particularly, Mars. A recent study employing a large number of conventional accretion simulations found the probability of forming a Mars-analogue object was 4-14% (Fischer & Ciesla 2014). The small Mars problem has recently resulted in arguments for a dramatic early reorganization of solar system architecture, as discussed in Section 3.2.2 below; Mars's rapid growth timescale, as measured by isotopic techniques (Section 2.1) provides another observational constraint on accretion models.

2. Key Constraints

In this section, we summarize key constraints on planet formation such as formation timing, mass distribution, bulk composition, isotopic constraints, and dynamical constraints. The observational constraints come mostly from the solar system, but we briefly discuss comparisons with extrasolar planetary systems in Section 2.6.

2.1 Timing

As will be seen below, one of the most important events in early solar system history was the loss of nebular gas. The timing of this event relative to the timescale of planet growth exerted a major control on the resulting solar system architecture (e.g. Morbidelli 2013).

An important constraint on the timing of gas loss comes from observations of young planetary systems. Young systems often show an infra-red excess, interpreted to be the signature of nebular dust (Chiang & Goldreich 1997). But the probability of seeing such an excess falls off steeply with system age, having a half-life of about 3 Myr (Haisch et al. 2001). The interpretation of this observation is that any dust not incorporated into bigger bodies is removed, likely via photoevaporation (Alexander et al. 2006). The same process(es) are assumed to remove the remaining gas, and thus a timescale for gas loss is established. Evidently, Jupiter and Saturn must have accumulated their envelopes prior to the loss of gas (see Section 3.1.3). As we will see below, a gas-loss timescale of ~3 Myr is consistent with the accretion history of Jupiter as inferred from isotopic data (see Section 4.1).

Radiogenic isotope systems (i.e., systems involving the decay products of radioactive nuclides) can be used to establish when solid planetary bodies formed or (more precisely) when large-scale chemical fractionation associated with planetary accretion and differentiation occurred. The earliest dated solar system solids are calcium-aluminium inclusions (CAIs), which are used to define the effective age of the solar system, 4567 million years (Ma) ago (Amelin et al., 2010; Connelly et al. 2012). CAIs are conventionally thought to have formed in high-temperature regions in the inner disk, so the fact that CAIs were recovered from a comet (Brownlee et al. 2006) indicates that at least some material was transported outwards over tens of AU.

Within ~1 Myr of CAI formation, asteroids with length scales of order 100 km had formed (Kruijer et al. 2014; 2017). This date is established from Hf-W isotope systematics, which constrain when the asteroids melted to form iron cores (Kleine et al. 2009), combined with models of how they were heated. The heat source is radioactive ^{26}Al, which has a short half-life (~0.7 Myr) but is very effective at melting bodies which formed within the first 1-2 Myr of solar system history (Hevey & Sanders 2006). Some of these differentiated bodies were subsequently broken apart by collisions to make iron meteorites (e.g. Bottke et al. 2006, Yang et al. 2007).

Over the period 2-4 Myr undifferentiated "chondrite" bodies formed (e.g. Kita & Ushikubo 2012, Schrader et al. 2016). These bodies are composed of agglomerations of mm-size spherical "chondrules", which were melted by an unknown mechanism, cooled slowly in the presence of gas (Cuzzi & Alexander 2006) and then aggregated into larger bodies along with a dust-like matrix (Budde et al. 2016b). Many asteroids have surface spectra which look chondritic (e.g. Vernazza et al. 2014); it is possible, however, that at least some of these asteroids are actually differentiated and just have a chondritic surface coating (Elkins-Tanton et al. 2011).

The Hf-W system provides the primary constraint on the growth timescale of larger inner solar system bodies (Kleine et al, 2009; Kleine & Walker 2017). These bodies generally consist of a silicate mantle overlying an iron core. If core formation is assumed to happen as a single event, isotopic measurements of the ^{182}W composition of the mantle can be used to determine the age of this event (called the "two-stage" model age). Separating the core from the mantle requires high temperatures; in large bodies such temperatures naturally occur during a giant impact (Rubie et al. 2007). Thus, core formation may be taken as a proxy for accretion.

In reality, core formation is not a single event, because terrestrial planets grow by multiple collisions. Furthermore, the degree to which iron and silicate undergo isotopic re-equilibration during collisions can also affect the inferred timescale (Deguen et al. 2014). This and the stochastic nature of accretion and core formation make it rather difficult to determine precise accretion timescales from the ^{182}W data. Nonetheless, the simple two-stage model age provides a firm lower bound on the accretion timescale, defining the earliest possible time when planet growth could have ceased. The two-stage model age for the Earth is ~30 Myr and for Mars is ~4 Myr (Kleine & Walker 2017); for Mars, the timescale for it to reach 90% of its final mass is about 3.6 ± 2 Myr (Dauphas & Pourmand 2011). It is thus apparent that small bodies can grow rapidly. Although the terrestrial tungsten signature could be due to rapid growth followed by a late, large impact (cf. Fig 19 of Kleine et al. 2009), it is equally likely that the Earth grew over a protracted period (tens of Myr). For the formation time of the Moon, there is a range of estimates, which predominantly use the time of lunar silicate differentiation as a minimum age of the Moon and, hence, the effective end of the Earth's accretion. Unfortunately, the timing of lunar differentiation is uncertain and estimates of ~70 Myr (Barboni et al., 2017) as well as ~200 Myr after CAIs (Borg et al., 2011) have been proposed. Thus, the most conservative approach is to assume that core formation of the Earth was essentially complete some time between 30 and 200 Myr after CAI formation. Figure 1 summarizes the available timing constraints.

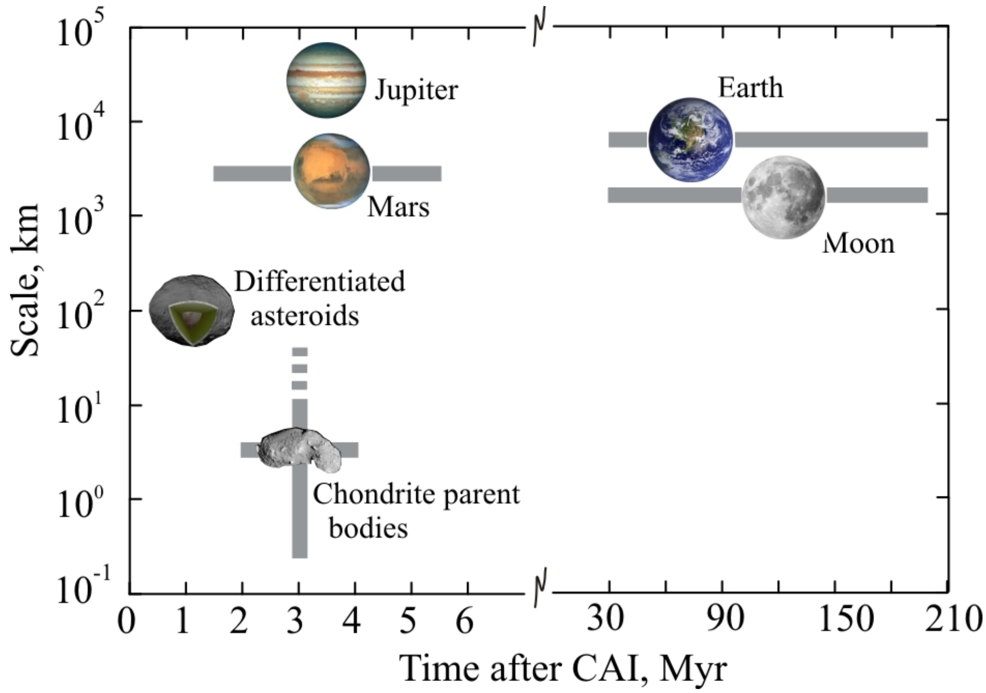

Figure 1. Inferred formation timescales and sizes of various objects of interest (see Section 2.1). The maximum size of chondrite parent bodies is currently uncertain. Jupiter's inferred formation timescale of 3-4 Myr is discussed in Section 4.1.

2.2 Mass & mass distribution

The inner solar system now consists of about 2 Earth masses (M_E) of rocky material. Beyond the asteroid belt, Jupiter (300 M_E) and Saturn (100 M_E) are mostly hydrogen but with large (~20 M_E) rock-ice cores. Uranus and Neptune (15 M_E) consist of a thin hydrogen envelope, with rock, ices and perhaps more hydrogen at depth.

By averaging the mass of each planet (after correction for gas loss) over an annular region the surface density distribution of the original nebula can be estimated (e.g. Hayashi 1981). Figure 2 plots one such distribution. Of course, if radial migration has occurred then the inferred distribution will be incorrect. Nonetheless, the derived 'minimum mass solar nebula' distribution has one very important feature: The region centered on the asteroid belt is very deficient in mass, and in recent years it has also been argued that Mars too has an anomalously low mass (see below).

A similar feature can be found further out: there appears to be a sharp edge to the Kuiper Belt, at about 47 AU (Trujillo & Brown 2001), beyond which the mass of objects present decreases very sharply. Nonetheless, some Kuiper Belts can be quite large, 1000 km or more in radius (McKinnon et al. 2017).

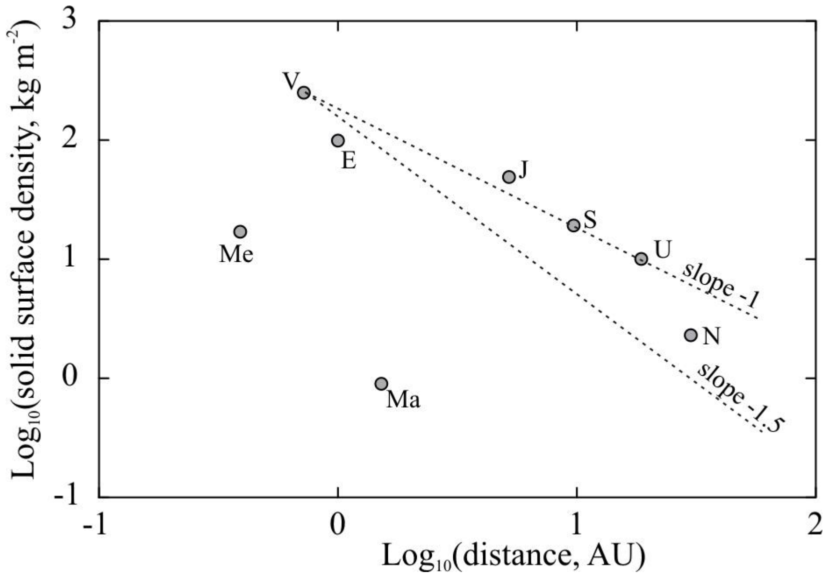

Figure 2. Minimum surface density of heavy elements (i.e. not H or He) as a function of distance. This is derived by smearing each planet's heavy elements over half the distance to each neighbour. For Jupiter and Saturn we assume a heavy element component of 25 and 20 M_E, respectively (see Section 2.3).

2.3 Bulk Composition

The inner solar system consists of bodies made mainly of rock and metal, but with much less carbon than most chondrites (Section 3.1.3). These inner bodies are depleted in more volatile elements: for instance, potassium (K) in the terrestrial planets is depleted by a factor of 3-10 relative to uranium (U), an element with similar geochemical behaviour but lower volatility. However, the K/U ratio does not show any systematic change with semi-major axis (McCubbin et al. 2012) and K isotopic fractionation - which should be large if the inner bodies had lost volatiles by evaporation - is only barely detectable (Humayun & Clayton 1995, Wang & Jacobsen 2016). The absence of clearly resolved K/U variations – with the notable exception of the Moon - may imply that any original compositional zonation was either small or efficiently mixed away.

The asteroid belt is mixture of spectrally "red" (primarily stony or S-type) and spectrally "blue" (primarily carbonaceous or C-type) asteroids, although some radial zonation is apparent (DeMeo & Carry 2014). This spectral difference may arise from different amounts of internal heating and/or volatile content, although this is uncertain (DeMeo & Carry 2014). It is tempting to assume that these two populations originate from different regions of the solar system, and indeed there is now isotopic evidence that this probably happened (Section 2.4).

The temperature structure of the solar nebula will have determined where water ice (and other volatiles) condensed. The location of this "snow line" probably changed with time (e.g. Garaud & Lin 2007). The solid surface density beyond the snow line was a factor of roughly two larger than immediately inside, with implications for the timescale of accretion. Objects drifting across the snow line will have lost ice via sublimation, resulting in a local pressure maximum which could also have affected accretion dynamics (Section 3.1.2).

Saturn and Jupiter are thought to have a substantial inventory of heavy elements (i.e. not hydrogen or helium), totalling about 5-20 and 7-25 Earth masses, respectively (Helled & Guillot 2013, Wahl et al. 2017). Some of these heavy elements reside in a central core, while the rest may have been entrained into the envelope. Both Jupiter and Saturn have H+He envelopes with higher concentrations of heavy elements (e.g. C, N, noble gases) relative to solar (e.g Hersant et al. 2004). The ice giants' thin hydrogen envelopes are further enriched in heavier elements relative to Jupiter and Saturn. Finally, the Kuiper Belt and beyond it the Oort cloud consist primarily of objects of mixed rock and ices, where not only H_2O and CO_2 but also more volatile species like N_2 , CO and CH_4 are also solid (Stern et al. 2015).

2.4 Isotopic constraints

Radiogenic isotopes provide several key constraints on the timescales of early solar system processes (Section 2.1). By contrast, stable isotopes (i.e., those that are neither consumed nor produced by radioactive decay) are powerful tracers to assess genetic links between different planetary objects. These stable isotope variations are nucleosynthetic in origin and arise through the heterogeneous distribution of presolar material within the disk.

A recent and important realization is that solid solar system materials come in two distinct isotopic "flavours", labelled carbonaceous (CC) and non-carbonaceous (NC). This was first proposed by Warren (2011) on the basis of O, Cr and Ti isotopes, but it has subsequently been shown to also hold for Mo (Budde et al. 2016a) and W (Kruijer et al. 2017). These different nucleosynthetic isotope compositions reflect the addition of a presolar component enriched in supernova-derived material to the CC reservoir (Budde et al. 2016a). Importantly, both the NC and CC reservoirs contain differentiated (e.g. iron meteorites) and undifferentiated objects (chondrites), which formed over a period of at least ~3–4 Myr (Kruijer et al. 2017). Consequently, the NC and CC reservoir must have remained isolated from each other for at least this period of time, presumably because they were spatially separated. To explain the inferred differentiation timing, both the NC and CC iron meteorites must have accreted within less than ~1 Myr after CAIs. Thus, the distinct isotopic compositions of the CC and NC reservoirs were already established by this time (Kruijer et al. 2017). As we will argue in Section 4.1 below, this isotopic dichotomy provides important constraints on the timing and process of planet growth, especially on the timing of Jupiter's formation.

Nucleosynthetic isotope anomalies can also be used to assess the nature and origin of the building material of the Earth and Mars, and the extent of radial mixing during accretion. The Earth predominantly accreted from bodies that formed within the NC reservoir (Budde et al. 2016a), with a smaller, though uncertain, contribution of CC material (Warren 2011, Dauphas et al. 2014). Isotopically the Earth shows an enrichment in "*s*-process" isotopes (those produced in red giant stars) relative to chondritic material. Of the chondrites, carbonaceous chondrites are more depleted in *s*-process isotopes than ordinary or enstatite chondrites, likely implying a heliocentric zoning of *s*-process matter in the accretion disk (Render et al. 2017). As all meteorites are characterized by an *s*-process deficit relative to Earth, no single group of meteorites nor a combination thereof can represent the building material of the Earth. There must be some *s*-process enriched material, which presumably was present closer to the Sun (Render et al. 2017) but is not present in our meteorite collections.

Owing to their different geochemical behaviour, Nd, Mo and Ru were added to the Earth's mantle at different stages of accretion (Dauphas 2017). The important observation from the isotopic data is that although Nd, Mo and Ru reflect different stages of Earth's accretion, they all are characterized by an *s*-process excess relative to meteorites. In fact, the Earth's mantle plots on Nd-Mo (Render et al. 2017) and Mo-Ru (Dauphas et al. 2004; Bermingham et al. 2018) isotope correlation lines together with meteorites, demonstrating that the isotopic nature and, hence, genetic heritage of Earth's accreting material has not greatly changed over time. This implies that the inner solar system was homogeneous (and thus well-mixed) during the early stages of Earth's accretion and/or that Earth's main building blocks averaged out existing small-scale heterogeneities. At least some such averaging is expected, given that the Earth likely accreted material from a much wider heliocentric distance than individual meteorite parent bodies.

The isotopic evidence for a relatively homogeneous feeding zone for Earth's building blocks raises the question of whether the isotopic composition of Mars is similar to or different from the Earth. Available isotopic data (for O, Ti and Cr) suggest that Mars is different from Earth and is more similar to enstatite and ordinary chondrites (Warren 2011). The Mo-Nd-Ru isotopic composition of Mars is not well known, and so it is currently unclear if Mars is also isotopically different from Earth for these elements. If further measurements confirm an isotopic difference between Mars and Earth for a more diverse set of elements, this may imply that mixing and homogenization in the inner solar system occurred after the formation of Mars at ~2-5 Myr.

Whereas the isotopic constraints discussed so far are mainly utilized to understand mixing processes during accretion, stable isotopes can also be used in a completely different manner. This is because some physical processes result in fractionation of the isotopes according to their mass. This mass-dependent fractionation can then be used to investigate for instance whether preferential loss of volatile materials has occurred (Section 2.3). Subtle variations in K (Wang & Jacobsen 2016), Mg (Hin et al. 2017) and Rb (Pringle & Moynier 2017) isotopic ratios have been used to argue for some evaporative loss of volatiles in the precursor bodies of terrestrial planets, though the details of this process are as yet poorly understood. One confounding feature is that some volatiles may have been added back in during “late accretion” (Section 3.2.5).

2.5 Angular momentum and dynamics

The solar system contains dynamical features which give clues to its early evolution. For instance, the excitation and gaps in the asteroid belt provide clues to how Jupiter’s orbit evolved (Section 3.2.2). Similarly, the low mass of the asteroid belt (Section 2.1) and the mixture of bodies there - which apparently came from quite different initial locations (Sections 2.3, 2.4) - may give clues to the prior location of Jupiter. The existence of the Neptune:Pluto orbital resonance suggests that the gas giants may have undergone migration (Section 3.2.1). And the Kuiper Belt contains widely-separated binaries, which provides a constraint on how they accreted (Section 3.1.2). We discuss all these issues below.

The spin states of the planets may also provide dynamical clues (Lissauer et al. 2000). Most spin in the same direction, except for Venus (which spins backwards) and Uranus (which is tilted on its side). Earth, Mars, Saturn and Neptune are all tilted, with obliquities of about 25-30^{o}. The spin rates of Venus and Mercury are controlled by solar tides and are thus not useful. Earth’s spin prior to Moon formation was rapid, perhaps 5 hours, but Mars has a slow spin rate (24h) that is not strongly affected by tides. Fast spins and tilted spin axes are likely signs of giant impacts (Section 3.2.4).

2.6 Comparison with other planetary systems

There is an enormous literature on exoplanets, more than 3000 of which are now confirmed. Analogues of the planets in our solar system would not be detectable with the current radial velocity, transit and direct imaging capabilities, except for a marginal detection of Jupiter. Nonetheless, although some exoplanetary systems, such as Kepler-90 and HD-10180, look quite similar to our own, most systems imaged so far look very different. Jupiter-mass planets are relatively rare, while super-Earths/sub-Neptunes (which our system lacks) are quite common (Howard 2013, Hatzes 2016). Furthermore, the majority of systems have at least one planet with a period less than that of Mercury, a region completely empty in our own System (Fressin et al.

2013). Since these planets are often found very close to resonant positions, this is a likely indicator of inward migration (Goldreich & Schlichting 2014). Many systems have Jupiter-analogues with high inclinations and/or eccentricities (Hatzes 2016), quite different from our own, dynamically “cold” system. Some strong dynamical process that our solar system never experienced must have happened in systems with these kinds of planets.

Understanding how our system came to look so different from the exoplanetary systems so far discovered represents a major theoretical challenge. We need to keep in mind that the specific details of how planets formed in our solar system could be different from those in a majority of planetary systems.

2.7 Summary

Table 1 provides a summary of the observational constraints discussed above. We will have recourse to this table when discussing how successful different planet growth scenarios are (Section 4). In particular, Sections 4.1 and 4.2 discuss the successes and failures of the Grand Tack and pebble accretion scenarios, respectively, in explaining these observations.

Timing (relative to CAI)	~100 km-scale bodies form in ~1 Myr
	Jupiter mostly grown by 3-4 Myr
	Mars forms at 3.5 ± 2 Myr; Earth forms 30-200 Myr
Mass	Asteroid belt and Mars have anomalously low mass
	Inner solar system ~2 M_E solids, outer solar system ~80 M_E heavy elements
Bulk composition	Asteroid belt is mixture of spectrally “red” and “blue” bodies
Isotopes	“Carbonaceous” vs. “Non-carbonaceous” reservoirs
	Late stage inner solar-system well-mixed (Ru-Mo-Nd isotopes)
	Volatile depletion in precursor terrestrial planet materials
Dynamics	Planets have tilted spin axes; Mars rotates slowly
	Asteroid belt and Kuiper Belt have dynamically excited populations
	Many Kuiper Belt objects are loosely bound binaries

Table 1. Summary of observational constraints. Jupiter’s growth time is discussed in Section 4.1.

3. Planetary Growth Processes

As explained above, we split our discussion of growth processes into two parts. The first part discusses “early” growth of objects, during which it is reasonable to assume that gas was present. This section includes pebble accretion and the potential formation of gas giants. At some point, the gas will be lost. The second part describes how subsequent “late” growth constructs the final terrestrial planets from precursor solid planetesimals. We consider both the case in which gas is still present, and the gas-free case.

3.1 Early Growth

The starting materials for planet formation are assumed to be the ubiquitous micron and sub-micron sized grains observed in the interstellar medium (Draine 2008). While there is some evidence for larger grains in the molecular clouds that are believed to collapse to form the stars and planetary systems (e.g. Pagani et al 2010), most of the growth from micron sized dust grains to planets must occur within the gaseous protoplanetary disk. In the next few sections we will review the general processes by which dust grains grow to large planetesimals and planets under the influence of the protoplanetary disk.

3.1.1 From Dust to Pebbles

The earliest stages of growth are believed to be relatively efficient. Dust grains collide at low velocities, forming fractal structures as the small grains grow though hit-and-stick collisions (Kempf et al 1999, Blum et al 2000). As conglomerates of grains grow larger, they begin to decouple slightly from the gas. As the grains decouple there are a number of processes that threaten to stifle a particle's growth; these processes are commonly referred to as growth "barriers." For example, as the growing dust conglomerates decouple from the gas they are able to attain higher relative mutual velocities e.g. due to differential response to turbulent eddies as well as different steady-state azimuthal and radial velocities. If they collide at too high a velocity than instead of sticking, the particles will fragment. Thus the particle's growth may be halted by reaching the "fragmentation barrier" (Blum & Munch 1993).

Additionally, due to the general radial gas density profile expected in protoplanetary disks, most regions of a gas disk are expected to be slightly pressure-supported and therefore rotate at a slightly sub-Keplerian velocity. As solid particles in the disk do not feel this pressure support they try to travel at the full Keplerian velocity. This causes the particles to experience a headwind and to lose energy and drift inwards towards the star. Therefore, if the drift timescale is shorter than the growth timescale a particle's growth will be halted due to this "drift barrier" (Weidenschilling 1977).

Even before a growing particle reaches either one of the above barriers it is possible that the growth may be halted by the process of compaction. As the particles collide at larger (but still sub-fragmentation) velocities, the initially "fluffy" particles will become more and more compact. If they become too compact then two colliding particles may not have enough contact points to stick, but they will still not have collided with enough energy to fragment. Thus their growth may be stalled at the so-called "bouncing barrier" (Zsom et al. 2010).

Each of these barriers occurs at different sizes in the disk because of the different gas densities, orbital velocities, and material properties of the grains. However, typical maximum sizes expected early in the disk evolution range from mm to cm sizes (e.g. Birnstiel et al 2012). Additionally, grains of these sizes are routinely observed in protoplanetary disks by observing them in mm and sub-mm wavelengths (Natta & Testi 2004, ALMA partnership 2015).

If silicate grain bonds are "sticky" enough, perhaps because the monomer grains are nanometer in size as opposed to the micron-sized grain more commonly assumed, than this fractal growth may be able to continue until very large sizes (Arakawa & Nakamoto 2016). Alternatively, "fluffy" ice grains may grow sufficiently rapidly that they become fully decoupled from the gas and no longer drift inwards (Okuzumi et al. 2012, Kataoka et al. 2013). In the latter case the planetesimals will grow via binary collisions to large km-sized fluffy aggregates with densities around 10^{-4} g/cc, which can then compress under self-gravity. However, it is not clear that the grains in a protoplanetary disk have the appropriate properties for this type of growth to occur.

3.1.2 Accumulation of Pebbles and Pebble Accretion

The fact that there is not a clear pathway for binary accretion to grow from dust size all the way to planetesimals (roughly 10-100 km-sized objects such as exist in the asteroid belt, classically considered as the starting point for planet formation models) seems rather problematic. However, once dust reached “pebble” (roughly millimeter-to-decimeter) sizes there are a number of proposed mechanisms to leap-frog over the intermediate sizes directly to large planetesimals.

There is even some observational evidence that this type of growth may have happened in our solar system. For example, Morbidelli et al (2008) argued that the size distribution in the asteroid belt cannot be matched by binary collisions between small km-sized planetesimals and instead must be due to the grinding of larger > 100km sized bodies (although see Weidenschilling (2011) for an alternative explanation). Perhaps more compellingly, the Kuiper Belt contains a number of very delicately bound binaries (Parker et al 2011). These binaries cannot be created by traditional binary exchange or chaotic capture mechanisms and they would be destroyed in a highly collisional environment, but they may have formed in a turbulent collapsing pebble cloud (Nesvorny et al 2010). Furthermore, the existence of ~1000 km-scale Kuiper Belt objects is hard to explain with conventional accretion: at such large distances and low surface densities, growth of such large objects is difficult (Stern & Colwell 1997).

Early on it was thought that particles may be able to settle into a thin mid-plane until they exceed the Roche density at which point they will no longer be sheared out by the gravitational force of the sun (Goldreich & Ward 1973). However, as the particles sediment turbulence will puff up the layer (Weidenschilling 1995), preventing this Roche density from being achieved unless dust concentrations are significantly enhanced (Sekiya 1998) or a sublimation front (snow line) is present (Ida & Guillot 2016). One process that has been demonstrated to robustly collect and concentrate pebbles beyond the Roche density is the “streaming instability” (Youdin & Goodman 2005). In this process, pebbles start to clump, forming clumps that move more slowly in the gas. Because nearby pebbles are still travelling faster they tend to pile up around the clump, which thus grows until it reaches the point at which it can gravitationally collapse and directly form a planetesimal. However, in order for the streaming instability to occur there must be a substantial quantity of appropriately-sized pebbles (more than roughly two times the nominal solar value of solids, all in pebbles). Because pebbles migrate very fast, the surface density of pebbles is expected to be much lower than the nominal solid surface density of the solar nebula. It is not yet clear that the streaming instability can form planetesimals generically in protoplanetary disks (Hughes & Armitage 2013, Krijt et al. 2016); favourable disk conditions (Drazkowska et al. 2016) or specific locations (Schoonenberg & Ormel 2017) may be required.

Fortunately there are other possible ways in which pebble-sized objects may accumulate to form planetesimals. If the disk is turbulent then small pebbles may be captured in small-scale turbulent eddies. These eddies will push the particles to the high pressure, outer edges of an eddy possibly exceeding the Roche density (Cuzzi et al. 2008,2010). Additionally, if the protoplanetary disk is not completely smooth there are other ways to collect particles. I n a typical disk one would expect the pressure gradient to decrease as one moves outwards from the central star (causing pebbles to drift inwards). However, if for some reason there is a local pressure maximum in the disk (either due to an azimuthally symmetric bump such as a zonal flow (e.g. Johansen et al. 2009, Simon et al 2012), change in disk viscosity (e.g. Kretke & Lin 2007, Lyra et al 2008), a “snow line” (Ida & Lin 2008)) or a long-lived vortex (e.g. Klahr & Bodenheimer 2006, Raettig et al 2015), the pebbles will instead move towards the pressure maximum. Alternatively, when icy pebbles of 10 cm sizes pass the snow line, they could disaggregate into small silicate grains plus vapour (Saito & Sirono 2011, Morbidelli et al. 2015). Because silicate grains are not sticky, they cannot grow and are coupled to disk gas. The rapid migration of icy pebbles and the slow radial migration of silicate grains results in pile-up of silicate grains just inside of the snow line, which could also lead to planetesimal formation (Ida & Guillot 2016). In this case, where planetesimals form most readily will depend on the inwards motion of the snow line, likely from >~ 5AU to <~ 1AU (Garaud & Lin 2007; Oka et al. 2011).

If a 100-1000 km planetesimal is able to grow by one of these mechanisms then it will effectively decouple from the gas and the gas drag that it experiences decreases by orders of magnitude. Unless something (such as a growing giant planet) scatters the planetesimal to highly eccentric orbits it will not experience a substantial amount of gas drag. Therefore planetesimal growth via mutual collisions will occur as described in Section 3.2.1 below.

However, there is still one possible mechanism by which gas may aid the growth of these proto-planets. Because none of the processes described above are 100% efficient, the end stage of the planetesimal formation process is likely to be a population of planetesimals embedded within a sea of pebbles. These pebbles are still drifting inwards rapidly, moving past the newly formed planetesimals. Johansen & Lacerda (2010) noticed that these pebbles were rather efficiently accreted by the planetesimals in their simulation. Analytically, Ormel & Klahr (2010) demonstrated that the capture cross-sections for these pebbles was very large, comparable to the Hill sphere for large bodies. The reason is straightforward: the planetesimal will cause the pebble to deviate from its original path, thereby increasing gas drag and reducing its energy. This reduction in energy can result in the pebble becoming bound to the planetesimal and ultimately colliding with it. Therefore, a planetesimal with > 100km size that has enough gravity to significantly deflect pebble orbits is required for this “pebble accretion” process to be efficient.

Lambrechts and Johansen (2012) recognized that pebble accretion was extremely rapid and could be very important in forming planets. While this process is naturally oligarchic, with all of the large planetesimals growing at roughly the same rate (Kretke & Levison 2014), Levison et al (2015a) demonstrated that as long as the timescale for pebble accretion was slow compared to the timescale for the growing planets to dynamically stir one another, a few cores can maintain a relative runaway growth to produce a few giant planet cores. This potentially solves one long-standing problem in planet formation theory: how the cores of giant planets can grow to the large sizes needed for efficient gas accretion (Section 3.1.3).

Pebble accretion may also have played a role in the inner solar system, though as discussed in Section 4.2 it may not be consistent with the observational constraints. The size of planetesimals that efficiently accrete pebbles depends sensitively upon the disk structure (Ida et al 2016). In a flaring disk (as is expected in the outer solar system based on the direct observation of silhouettes of flaring protoplanetary disks (e.g. Burrows et al 1996, Padgett et al 1999, Smith et al 2005)) then one needs a larger planetesimal in order to accrete pebbles as one moves farther out in the disk. This may explain why planet formation did not continue into the Kuiper Belt (Lambrechts and Johansen 2012). If the inner disk is flaring as well, for example due to the changing opacity around the snow line, then the low mass of Mars and the asteroid belt could also be explained by pebble accretion if inward drifting pebbles are disrupted at the snow line (Levison et al 2015b). It has been proposed that chondrules on asteroids may have been accreted onto existing planetesimals by the process of pebble accretion (Johansen et al 2015), in which case gas must have been present when this occurred. However in this case one might expect that the interior of an asteroid (the primordial planetesimal) would have a different composition from the accreted chondrule layer, so it may be surprising that asteroid families, believed to be the product of the disruption of a single asteroid, appear so uniform in composition (Masiero et al 2015).

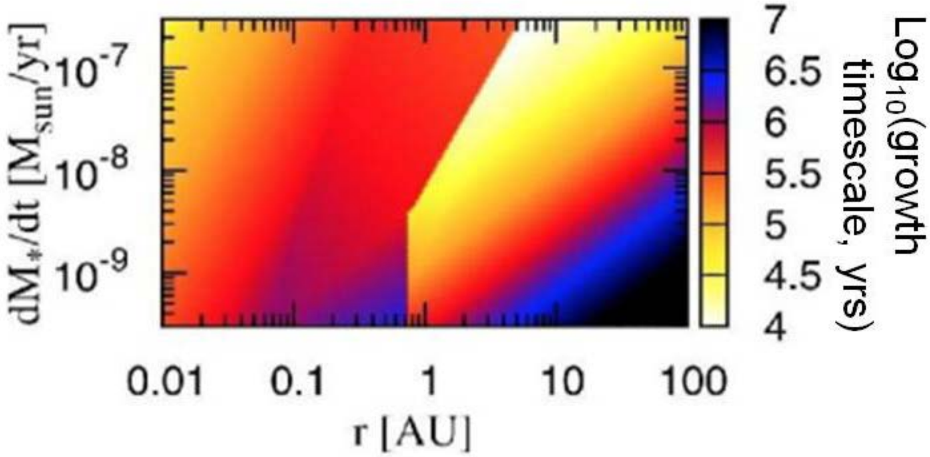

Figure 3. An example of how the timescale for growth by pebble accretion depends on the structure of the protoplanetary disk. Estimates of the timescale for a planet to grow by pebble accretion (log scale in years). Reproduced from Ida et al. (2016). The discontinuity in the center of the figure indicates the position of the snow line in the evolving protoplanetary disk. Note that growth is more rapid immediately beyond the snowline.

The theory of pebble accretion is only a few years old, so the details are still unclear. But if it is true that dust growth naturally leads to pebble-sized particles and that planetesimal formation is relatively hard (especially early in the protoplanetary disk lifetime), then pebble accretion may have served an important role in shaping our, and other, solar systems.

3.1.3 Gas Giant Growth

The planetary mass budget is dominated by Jupiter and Saturn, so it is obviously important to assess how and when these bodies formed. Given the gas loss timescale of ~3 Myr (Section 2.1), formation must have been early. There are two possible modes of formation (Youdin & Kenyon, 2013).

The first is termed “core accretion” (e.g. Mizuno 1980, Stevenson 1982, Bodenheimer & Pollack 1986). A planet embedded in the gas disk will bind some gas in an envelope. The envelope mass will increase as the planet grows, and the temperature of the envelope depends on the balance between planetesimal accretional heating and radiative cooling. At some critical mass, cooling will begin to dominate and the envelope will collapse. At this point, a runaway occurs, with the now-denser planet accreting yet more gas, rapidly producing a gas giant. The critical mass depends on the planetesimal accretion rate, but is typically ~10 M_E. A major advantage of pebble accretion is that it can easily grow such a planet before the gas dissipates.

The main alternative is “gravitational collapse” (Boss 2000), whereby a gravitationally unstable gas disk might fragment into objects that survive as gas giants. This mechanism seems very likely to be responsible for the distant gas giants that have been directly imaged in some systems (e.g. Kalas et al. 2008). However, forming Jupiter (which is relatively close-in and small) seems to be very difficult (Kratter & Lodato 2016).

Assuming that Jupiter formed by core accretion, we are presented with a paradox. In this scenario, at about 5 AU a ten Earth-mass planet must have grown in less than ~3 Myr. And yet the Earth, at 1 AU, apparently took more than 30 Myr to finish growing (Section 2.1). Somehow Jupiter managed to avoid this delay and grow a 10 M_E core in a few Myr or less, despite the fact that the orbital timescale was longer and the disk surface density lower than at 1 AU.

Pebble accretion may provide an explanation for these different accretion rates, but it relies on poorly constrained assumptions about the pebble and planetesimal sizes. In order for pebble accretion to form different-sized bodies in the inner and outer solar system, there needs to be a change in the properties of either the planetesimals or the pebbles (or both) at the snow line. If rocky pebbles are smaller than icy pebbles, then the factor of two difference in mass flux available to the inner and outer solar system due to the sublimation of ices combined with the inefficient accretion of the small pebbles can lead to a solar system dichotomy, where objects only grow to Mars masses in the inner solar system while they grow to tens of Earth masses in the outer solar system (Morbidelli et al. 2015). Alternatively, if one asserts that planetesimal formation naturally produces smaller planetesimals in the inner solar system for some reason, pebble accretion will also be inefficient there. Additionally, the fact that the terrestrial planets are remarkably carbon-poor when compared to carbonaceous material may imply that something prevented even the refractory material from the outer solar system from drifting inwards into the inner solar system (Levison et al. 2015b). We discuss this issue further below (Section 4.2).

3.1.4 Gas-Driven migration

Once a planet has grown (either through classic planetesimal growth or through pebble accretion), a new mode of interaction with the protoplanetary disk emerges: tidal migration. These larger protoplanets begin to launch spiral waves in the protoplanetary disk. Ward (1997) divided these tidal interactions into two classes: if a planet is too small to cleanly open a gap in a protoplanetary disk it experiences type I migration, and if it is large enough to open a gap it experiences type II migration. The existence of “hot Jupiters” and near-resonant exoplanetary pairs (Section 2.6) is strong evidence that some kind of migration actually occurred.

An embedded planet will feel strong torques from the disk interior to its location as well as the disk exterior to it (and from gas co-rotating with the planet). These inner and outer torques are in opposite directions and roughly cancel each other; however there is a small imbalance in the torque that can cause these bodies to migrate extremely rapidly. For example, in a classical calculation by Tanaka et al. (2002) it was found that an Earth-sized planet initially at 5 AU would migrate inwards toward the Sun in less than a million years. While this is not too problematic for forming the terrestrial planets (which likely only reached 1/10th that size while the gas disk was still around, and thus had a 10 times slower migration rate), this short timescale is extremely problematic for forming the cores of the giant planets, which must grow 10 times larger. Fortunately, because type I migration involves a balance of these inside and outside torques, relatively small changes of the structure around the disk can change the speed and even reverse the direction of migration. For example, if a disk is thick enough that it only cools slowly, then as the gas travels along horseshoe streamlines in the vicinity of the planet, the torques of the planet will be modified, potentially leading to outward migration under some conditions (Paardekooper & Paplaloizou 2009). Furthermore, accretion onto the protoplanet itself may locally heat up the disk, changing the torque profile and causing the planet to reverse its migration direction (Benitez-Llambay et al 2015). Therefore the true speed and direction of type I migration is likely a complicated process that is sensitive to the poorly constrained details of protoplanetary disk structure.

One might hope that pebble accretion is fast enough such that a growing protoplanetary core may not migrate substantially while it is too small to open a gap. However, Bitsch & Johansen (2016) found that under commonly-assumed disk properties Jupiter's core may still need to have begun growing in the distant solar system (beyond 20 AU) in order to arrive at its current location. While this large scale migration may solve the specific problem of Jupiter, it does beg the question of why no giant planet formed closer in, to end up in the inner Solar System today, or what happened to the potentially quite large population of planetesimals resonantly trapped by the migrating Jupiter, presumably to be left in the present-day asteroid belt.

If a protoplanetary core can successfully grow large enough to open a gap (Crida et al 2006) then it will migrate at the slower “type II migration rate.” In this circumstance a planet simply migrates along with the gaseous protoplanetary disk, typically modeled as a diffusive process. The planet is expected to continue to migrate as long as the planet is less massive than the local mass of the gas disk (Lin & Papaloizou 1986). Once the planet grows large enough, or the disk loses enough mass, then the planet will cease to migrate. So if a giant planet forms late enough in the disk evolution then it is not expected to migrate substantially (Thommes et al 2008).

Under certain circumstances it is also possible to reverse the direction of type II migration. Masset & Snellgrove (2001) found that if a Jupiter and a Saturn-mass planet are close enough that the gaps that they open up overlap, then the two planets will cease migrating inwards and may even migrate outwards. This idea was further developed as the “Grand Tack” in which Jupiter migrated inwards, was “caught” by the faster migrating Saturn, and then (when Jupiter reached 1.5 AU) the migration was reversed and the two planets migrated outward to beyond 5 AU (Walsh et al 2011). This model is discussed in more detail in section 3.2.2.

Recent high-resolution simulations (Duffell et al. 2014, Kanagawa et al. 2018), however, have demonstrated that type II migration is not in fact determined by diffusive disk evolution. In particular, Kanagawa et al. (2018) argue that type II migration is simply type I migration controlled by the gas surface density in the gap. The consequences of this change in thinking have yet to be explored.

3.2. “Late” Growth

In this section we discuss how planetesimal accretion proceeds in the absence of gas. Figure 4 provides a summary sketch showing the different stages of growth.

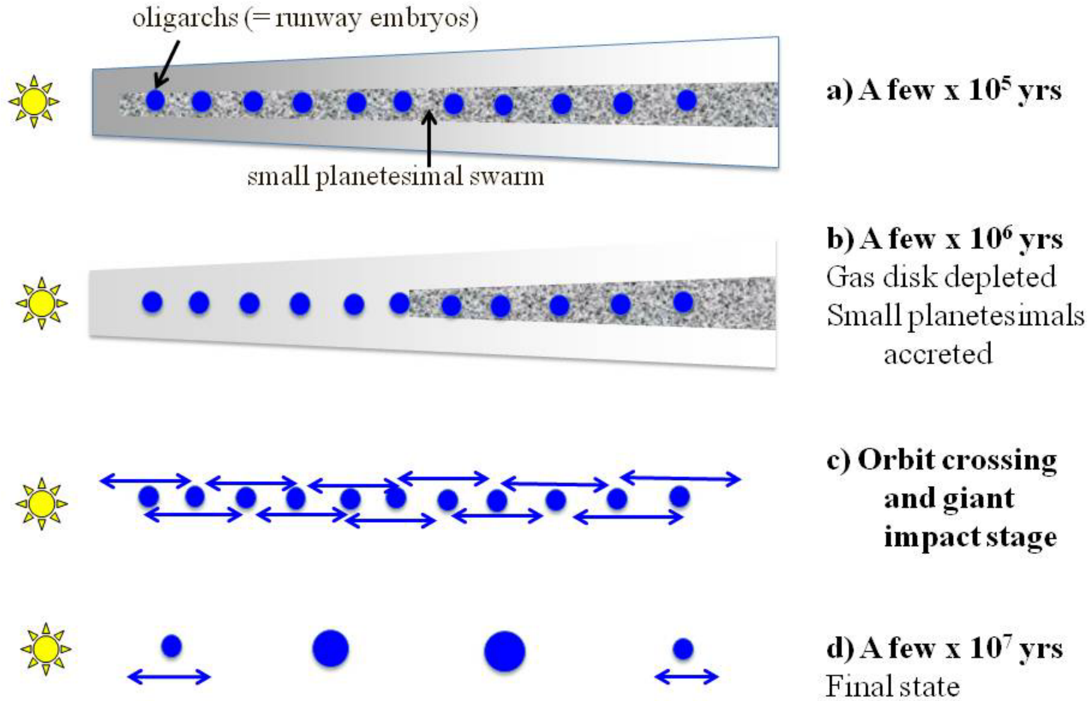

Figure 4. Cartoon of the later stages of solid-body accretion in the inner solar system.

3.2.1 Isolation mass and migration

The classical model of planetesimal accretion, which neglects migration, is as follows. In the early stages, the growth mode of planetesimals is "runaway" growth, where larger planetesimals grow more rapidly than the others (e.g., Wetherill & Stewart 1989, Kokubo & Ida 1995). In the later stages, the smaller embryos catch up with the larger ones, resulting in similar-sized embryos with orbital separations more than $5r_H$ (r_H is the two-body Hill radius defined by $(m_1+m_2/3M^*)^{1/3}a$, where a represents semi-major axis, m mass and M^* the stellar mass), while most planetesimals remain small. This stage is called "oligarchic" growth (Kokubo & Ida 1998). Because gravitational interactions with disk gas (Ward 1993) and dynamical friction from nearby planetesimals (Kokubo & Ida 1998) strongly damp the orbital eccentricities of the oligarchs, their orbits are kept in stable, nearly circular orbits. Through oligarchic growth, a bi-modal system of oligarchic embryos and a planetesimal swarm is formed. Because embryos grow much faster in the runaway phase than in the oligarchic phase, the transition is immediate once planetesimal accretion starts. The formation timescale of Mars-size embryos is ~ a few x 10^5 yrs at 1AU for the minimum-mass solar nebula (MMSN) model (Hayashi 1981) and it is approximately proportional to $m^{1/3}a^3$.

The final mass of the embryos in the presence of disk gas ("isolation" mass) is estimated as the total mass of planetesimals in their "feeding zone", with a width of ~$10r_H$. Because most of the planetesimals would have already accreted to the embryos in this phase, the eccentricity damping by disk gas is responsible for orbital stability of the embryos. For the MMSN, the isolation mass is ~0.15 M_E at 1 AU (Kokubo & Ida 1998) and it increases with orbital radius. The next stage of growth is via collisions between embryos. This requires orbits to become non-circular, which means this stage does not occur until after the disk gas (which damps eccentricity) is depleted (Ida & Lin 2010). Mercury and Mars could be embryos that avoided collisions during the giant impact stage. Indeed, the early accretion of Mars deduced from Hf-W chronology (Section 2.1) supports this scenario. In the MMSN model, a power-law mass distribution is assumed (Figure 2). The isolation mass for a locally concentrated planetesimal distribution (Hansen 2009) would be much larger.

If type I migration is taken into account, planets would start to migrate before they attain the isolation mass at >~ 1 AU (Ida & Lin 2010). While the accretion timescale increases with the planet mass as $t_{acc} \sim m^{1/3}$, the type I migration timescale decreases as $t_{mig} \sim m^{-1}$. Migration starts when the mass m exceeds a threshold value ~ 0.1 $(a/1\mathrm{AU})^{-1}$ M_E, at which point $t_{mig} < t_{acc}$. As m increases, migration becomes more effective compared to accretion. Because planetesimals in inner regions have already been cleared, type I migration would thus cause growth to stop, except for planet-planet mergers (which are rare).

Outward migration due to non-isothermal torque occurs in viscous heating-dominated disk regions rather than irradiation-dominated regions, and for intermediate planetary mass (Paardekooper et al. 2011; Baruteau & Masset 2013). In this case, planets may converge to the boundary between viscous and irradiative regions and can attain masses beyond the isolation mass.

Isolation mass in the presence of pebbles

In the case of pebble accretion (as described in section 3.1.2), the idea of "feeding" zones does not make sense, because pebbles migrate all the way through the disk. When a planet becomes large enough to make a (partial) gap in the disk, the positive radial pressure gradient near the outer gap edge inhibits migration of pebbles due to aerodynamic gas drag. Lambrechts et al. (2014) estimated the gap-causing mass as ~ several M_E at 1 AU (it also increases with orbital radius). This is independent of solid surface density. This critical mass is much larger than the masses of the current terrestrial planets in our solar system. Pebble accretion is halted before a planet acquires the critical mass, if the pebble flux from outer regions is truncated by consumption of all the solid materials there (Ida & Guillot 2016), or by formation of a large planet, such as Jupiter, located in an outer region (Morbidelli et al. 2016). We also note that Bitsch et al. (2018) proposed a new formula for the pebble isolation mass that depends on the disk turbulence, and which can yield much smaller isolation masses than in Lambrechts et al. (2014).

As in the case of planetesimal accretion, when a planet acquires a threshold mass, type I migration is faster than accretion and planets migrate rather than continuing to grow at their original locations. Beyond the snow line, icy pebbles migrate faster than the planet, so the accretion timescale is not affected by the migration. Thus, there will still be a maximum planetary mass at a given orbital radius. If the pebbles cross the snow line, the ice sublimates and smaller silicate grains remain. Because such small grains are coupled to the disk gas, what then happens depends on the level of turbulence in the disk and the accretion rate; further study of this issue is required.

Planetesimal-driven migration

Note that even after the disk gas is depleted, planetesimal-driven migration could occur, if the total mass of residual planetesimals is comparable to the planet's mass (Ida et al. 2000, Kirsh et al. 2009, Minton & Levison 2014). If planetesimals are more dense in one direction, the planet will scatter these planetesimals in the opposite direction and thus move towards the denser planetesimal region. Thus, this kind of migration requires an initial asymmetry in the local planetesimal mass distribution, but once migration begins it is self-sustaining. In the case of multiple giant planets, planetesimal scattering drives the outer less massive planets (Uranus and Neptune) outwards. This kind of outwards migration is likely responsible for the Neptune:Pluto 3:2 resonance (Malhotra 1993) and may have caused the so-called Late Heavy Bombardment (Section 3.2.5).

3.2.2 Effects of giant planets and migration

Gravitational perturbations from the gas giants, Jupiter and Saturn, are so strong that they can affect the orbital configurations of the whole planetary system. In the case of the asteroid belt, bodies are almost completely cleared in the proximity of Jupiter (beyond 3.2 AU), except the Hilda group near the 3:2 mean-motion resonance with Jupiter (Lecar et al. 1992). Even in the regions relatively far from Jupiter, the effects of first-order (j:j-1) mean-motion resonances are strong. For bodies in eccentric orbits, 2nd order (j:j-2) and 3rd order (j:j-3) resonances are also important (Murray & Dermott 2000). Small bodies trapped at an isolated resonance with a single planet are usually orbitally stable. An example is the Hilda family. But, when the eccentricities of bodies in a mean-motion resonance are excited close to unity or start crossing another planet (Mars, in the case of the asteroid belt), their orbits become unstable. Thereby, asteroids are depleted at the 3:1, 5:2, etc. resonances (Murray & Dermott 2000). Close to Jupiter, first order resonances with finite widths overlap and the orbits become chaotic and undergo close encounters with Jupiter (Murray & Dermott 2000).

Note that asteroid orbits are stable over long timescales except for the orbits near Jupiter and those in resonances. The surface density of asteroids in the stable regions is still at least 10^2 times lower than that of the MMSN (Fig 1). Furthermore, the orbital eccentricities and inclinations of asteroids in the stable regions are generally very high and Jupiter's perturbations in its current orbit cannot be responsible for this dynamical excitation (Murray & Dermott 2000). Something must therefore have happened in the asteroid belt during the solar system formation stage.

Grand Tack model

One possibility, termed the "Grand Tack" (Walsh et al. 2011) is that Jupiter underwent inwards (type II) migration, and then reversed course and migrated outwards once Saturn had grown to an appropriate size. The entire in-and-out migration thus happened prior to gas depletion.

In a disk-planet system, angular momentum is globally transferred outward and mass is transferred inward (Lynden-Bell and Pringle 1974). However, if planets can continue to acquire angular momentum from a local region of disk gas that is inwardly migrating, they can migrate outward. In the standard picture of type II migration, a single planet opens up a clean gap in the disk, also halting the inwards radial drift of solid material (Lambrechts et al. 2014). The planet then always loses angular momentum and migrates inward together with the local disk gas. However, if the disk mass is smaller than that of proto-Jupiter, but larger than that of proto-Saturn, the latter will migrate inwards faster. The two bodies will then ultimately open up a common gap and under some disk conditions, outwards migration then occurs (Masset & Snellgrove 2001). This happens if Saturn's mass is not large enough to make a deep gap, while Jupiter makes a clean gap. In this case, disk gas can enter the gap from the outer region (Saturn's side) and crosses the gap through interactions with Saturn and Jupiter. Jupiter and Saturn then gain angular momentum from the gap-crossing flow and migrate outward. In order for this outward migration to happen, i) the disk mass must be larger than the total mass of Jupiter and Saturn, and ii) the disk thermal and viscous conditions must be tuned such that a gap by Saturn is not clean and gap-crossing flow is allowed.

Walsh et al. (2011) manually set up the early-inward and later-outward migration of Jupiter and Saturn to study its effects on small bodies in the early solar system. If the turn-around ("tack") location is 1.5-2.5 AU, the asteroid belt is depleted by Jupiter's perturbations. This same scenario can also explain the small size of Mars (Section 2.2). The inwards motion of Jupiter causes a truncated disk of solids; Hansen (2009) showed through N-body simulation that such a truncated disk nicely reproduces the orbital configurations and masses of the terrestrial planets. Walsh et al. (2011) did not include type I migration, but Brasser et al. (2016) did similar calculations with type I migration to find that the overall results are similar.

The Grand Tack model also explains the spectral differences between S-type and C-type asteroids (Section 2.4). During the outward migration of Jupiter after the tack, it scatters inward icy bodies that were originally located beyond Jupiter's orbit, which correspond to C-type asteroids (the presumed parent bodies of the carbonaceous meteorites), while S-type asteroids (the presumed parent bodies of the non-carbonaceous meteorites) are left-over asteroids in their original locations. Because the asteroids are scattered by Jupiter, the high eccentricities and inclinations of the asteroids are also explained.

The model, however, is not without problems. For example, outward migration is only supported for a specific set of initial conditions (D'Angelo & Marzari 2012) and may not be universal (Zhang & Zhou 2010). Furthermore, as mentioned in section 3.1, a new model of type II migration has been proposed (Kanagawa et al. 2018) which may alter (or invalidate) the original Grand Tack assumptions. More recently, Levison et al. (2015b) and Drazkowska et al. (2016) proposed that pebble accretion may also explain the low mass of Mars (see Section 3.1.2), though pebble accretion does not obviously explain the mix of S- and C-types in the asteroid belt, nor its dynamical excitation.

Another potential way of clearing out the asteroid belt is "sweeping secular resonances" due to progressive disk gas depletion (Ward 1981, Nagasawa et al. 2000, Zheng et al. 2017). When the precession frequency of the argument of periastron of an asteroid coincides with that of the giant planets, the eccentricity of the asteroid secularly increases to high values. This is called a "secular resonance" (Murray & Dermott 2000). As the gas disk is depleted, the location of the secular resonance migrates ("sweeping secular resonance"). The eccentricities (and inclinations) of the small bodies are excited by the secular resonances and then are damped by aerodynamic gas drag after the passage of the resonances. Because eccentricity damping also results in inward migration, small bodies in a certain range of semimajor axis are removed, while relatively large bodies that are insensitive to aerodynamic gas drag remain with high eccentricities and inclinations (Nagasawa et al. 2005). While sweeping secular resonances can account for the clearing and the orbital excitations of asteroid belt, this model does not explain the observed mixing of C-type and S-type asteroids.

3.2.3 Giant impacts

Through oligarchic growth, embryos are formed with orbital separation ~10 r_H in a gas-free environment (Kokubo & Ida 1998) and with 5-7 r_H in the presence of gas-driven eccentricity damping (e.g., Ogihara & Ida 2009). If type I migration is included, embryos are often trapped at mean-motion resonances in inner disk regions. The separation is wide enough to secure their orbital stability as long as their orbital eccentricities are small. As long as gas is present, it keeps the eccentricities damped, but once the gas is depleted, eccentricities increase leading to orbital crossing and giant impacts (e.g., Kominami & Ida 2002). This represents the final stage of terrestrial planet formation, and typically takes many tens of Myrs to complete (Agnor et al. 1999, Chambers 2001).

During orbit crossing, orbital eccentricities of embryos are excited up to ~ v_{esc}/v_K where where $v_{esc} = (2GM/R)^{1/2}$ and v_K are the surface escape velocity of the largest embryos undergoing the orbit crossing and the local Keplerian velocity, respectively. The eccentricities are $e \sim 0.3$ for Earth-mass bodies at $a \sim 1$ AU. They are proportional to the physical size of the bodies and inversely proportional to square root of the orbital radius. Because of the excited eccentricities, the final orbital separations of the planets are similar to *ea* (Kokubo et al. 2006).

N-body simulations show that the eccentricity of a post-collision body is usually significantly smaller than ~ v_{esc}/v_K (Kokubo et al. 2006). This “collision damping” occurs because collisions occur preferentially between bodies with opposite directions of pericenters (Ida & Lin 2010, Matsumoto et al. 2015). The timescale for the next orbital instability to occur depends sensitively on the orbital separation scaled by Hill radius (Chambers et al. 1996). When merging events occur, the separation increases and the timescale jumps up. Eventually, the instability timescale attains values far beyond the main sequence lifetime of the host star and the system reaches a very stable state (not a meta-stable state) (Ida & Lin 2010).

Although collision damping is effective, the simulation results still show the eccentricities of the final model planets are larger than the free eccentricities of the terrestrial planets in the solar system (Agnor et al. 1999, Chambers 2001). Other mechanisms such as dynamical friction from the residual disk gas (Kominami & Ida 2002) or residual planetesimals (O’Brien et al. 2006, Raymond et al. 2006) must further damp the eccentricities.

Most accretion simulations assume that if two bodies collide, they merge. But in reality only about half of all collisions are expected to result in mergers (Asphaug 2009, Kokubo and Genda 2010), and most collisions are likely to produce some unbound fragments. Some models have investigated the effect of including bounces or fragmentation on accretion; Kokubo & Genda (2010) showed that the accretion timescale and orbital configurations and masses of the final planets are not significantly affected while Chambers (2013) showed that accretion takes about twice as long to complete, which tends to drive the final tungsten anomaly down (Dwyer et al. 2015).

Because the pebble isolation mass is significantly larger than an Earth mass at 1AU, it is possible that the terrestrial planets were formed mostly through pebble accretion. But this introduces at least two problems. First, if the terrestrial planets formed without experiencing giant impacts, then the tilt of the Earth, the existence of the Moon, and Mercury’s thin mantle all require some other explanation. Furthermore, the prolonged accretion timescale of the Earth then becomes very hard to explain. In short, the terrestrial planets show no strong evidence for pebble accretion.

3.2.4 Effects of giant impacts

The giant impact stage of accretion typically involves collisions between comparably massive objects. For planetesimal impacts, the impact velocity is estimated by $v_{imp} \sim (e^2 v_{Kep}^2 + v_{esc}^2)^{1/2}$. In a dynamically-excited disk (e.g. during the Grand Tack) eccentricities and thus collision velocities will be higher. High-velocity collisions play a major role in determining the final state of the planet.

Collisions can remove material from the target, which may be the explanation for the thin mantle of Mercury (Benz et al. 2007) or the existence of the Earth's Moon. The collisions are also usually sufficiently energetic to cause widespread melting, perhaps leading to primordial magma "ponds" or magma oceans (Tonks & Melosh 1993). On the other hand, in the other extreme case, pebble accretion, magma oceans may not form. When a planet is embedded in a protoplanetary disk gas, it should attract some fraction of the disk gas to form a primordial H-He atmosphere (Ikoma & Hori 2012). Because of gas drag from the H-He atmosphere, the pebble impact velocity should be the terminal velocity and direct impact melting is unlikely for Earth-size planets. Pebbles can also be ablated (Alibert 2017). The impact energy of pebbles is deposited to the atmosphere rather than the surface. Detailed analyses of how pebble accretion would affect terrestrial planet interiors and atmospheres have yet to be carried out.

Once the gas disperses, a growing planet might retain a primordial atmosphere (if it is big enough) or store some of the gas in a magma ocean. On the other hand, subsequent growth via impacts will cause atmospheric erosion, with an efficiency depending mainly on the escape velocity (Shuvalov 2009). The noble gases of the terrestrial planets can in principle be used to probe these processes, but the data are hard to interpret (e.g. Zahnle et al. 2007).

Collisions can also strongly affect the direction and rate of spin (Agnor et al. 1999). Because of the stochastic nature of the giant impacts, planetary spin vectors are expected to be randomized. At least for solid planets, accretion models show that spin rates are typically fast (close to breakup), although these rates are probably overestimates because the models neglect angular momentum loss via fragmentation (Kokubo & Genda 2010). The slow rotation rate of Mars could simply be a low-probability outcome, but it might also be a signature of either pebble accretion or oligarchic growth.

3.2.5 Accretion tails – late veneer and Late Heavy Bombardment (LHB)

Although the main stage of terrestrial planet accretion probably ended by around 100 Myr after CAIs, leftover debris continued to impact (as shown by planets' cratered surfaces). One way of defining the effective end of accretion is to associate it with the end of core formation. Core formation will have very effectively removed the highly siderophile elements (HSEs; the platinum-group elements, Re and Au) from the mantle, because of their extreme tendency to partition into metal. The HSE abundances estimated for the mantles of the Earth and Mars are higher than expected for core-mantle partitioning, however (Walker 2009). This, and the broadly chondritic relative abundances of the HSEs in the mantles has led to the idea that the HSE mantle abundances reflect the addition of chondritic material *after* core formation ceased. This process is termed "late accretion" and the material that has been added is often referred to as the "late veneer" (see e.g., Walker, 2009). For the Earth, HSE measurements (Becker et al. 2006) suggest the late veneer represents ~0.5% of the Earth's mass (equivalent to a single object about 1000 km in radius). At Mars, the late veneer mass fraction is similar to the Earth's, but for the Moon the late veneer fraction is much smaller than expected, about 0.02% (Bottke et al. 2010; Day and Walker 2015). Although in principle this lack of late veneer could be due to late Moon formation, it would require the Moon-forming impact to not disturb the Earth's relative HSE concentrations, which seems unlikely. A more likely explanation for this discrepancy is that the late veneer was added stochastically, in large bodies, and that the Moon was not hit by such a body (Bottke et al. 2010). Although not unique (e.g. Morbidelli et al. 2018), this explanation is consistent with the ~25 ppm ^{182}W excess measured for the Moon, which is exactly the Earth-Moon ^{182}W difference expected for disproportional late accretion (Kruijer et al. 2015; Touboul et al. 2015; Kruijer and Kleine 2017). The large, late-impacting bodies presumably represent the final surviving planetesimals, and their isotopic makeup must have resembled the proto-Earth's, based on the Ru-Mo isotopic evidence (see section 2.4). As the Ru isotopic composition of Earth's mantle entirely reflects late accretion and is distinct from known meteorites, and because Earth's mantle plots on the Ru-Mo correlation (see Section 2.4) the late veneer most likely derives from the same population of bodies as the main building blocks of the Earth (Fischer-Gödde & Kleine, 2017).

Cratered lunar surfaces and samples returned by the Apollo missions were used to argue for a late “spike” in the bombardment flux at ~3.9 Ga (Tera et al. 1974), although the evidence for such a spike has been repeatedly questioned (e.g. Stoffler et al. 2006, Bottke & Norman 2017). If real, one possible explanation for a spike is planetesimal-driven migration of Jupiter (Section 3.2.1) causing it to encounter a 2:1 resonance with Saturn (Tsiganis et al. 2005) – the so-called “Nice model”. The effect is an instability which scatters many outer solar system planetesimals into the inner solar system, potentially explaining the hypothesized impact spike (Gomes et al. 2005). However, this mechanism has difficulty explaining the structure of the asteroid belt (Morbidelli et al. 2010). Also, the timing of the 2:1 resonance passage depends on the unknown initial conditions, so the match with the inferred impact spike is not a strong argument in favour of the hypothesis. In any event, the late spike does not represent a significant addition of mass to any of the terrestrial planets, though, if real, it may have caused resurfacing of the terrestrial planets (Marchi et al. 2014) and widespread destruction of the inner moons of the gas giants (Movshovitz et al. 2015).

4. Discussion, Conclusions, Future Work

At the start of this article (Section 1.1) we presented three puzzles: overcoming the metre-size barrier; forming the gas giants; and explaining the small mass of Mars. While the first of these puzzles still has some details to be worked out, the streaming instability, or another mechanism involving the direct formation of planetesimals from gravitationally unstable pebble clouds, appears to solve the most pressing problems (Section 3.1.2). The second and third puzzles are not yet resolved, and have given rise to new ideas, notably pebble accretion and the Grand Tack. Below we will focus on how well these new ideas work to explain the observations; Table 2 summarizes the current state of play. We will also identify some outstanding issues and questions.

	PRO	CON
Grand Tack	Asteroid belt and Mars have anomalously low mass	Earth forms 30-200 Myr
	Asteroid belt is dynamically excited and a mixture of spectrally “red” and “blue” bodies	
	“Carbonaceous” vs. “Non-carbonaceous” reservoirs	
	Mars forms at 3.5 $\pm$ 2 Myr	
Pebble Accretion	Many Kuiper Belt objects are loosely bound binaries	Earth forms 30-200 Myr
	Jupiter mostly grown by 3-4 Myr	
	Mars spins slowly	

Table 2. Score-card for pebble accretion and Grand Tack based on observational constraints from Table 1 (see text).

4.1 Grand Tack

Jupiter’s inwards migration (the Grand Tack) was originally introduced to explain the small mass of Mars and the compositional diversity of the asteroid belt. At roughly the same time, but quite independently, it was recognized that all chondrites, achondrites and iron meteorites come in one of two “flavours” (carbonaceous (CC) and non-carbonaceous (NC) - Section 2.4). It has recently been demonstrated (Kruijer et al. 2017) that this division into two flavours cannot reflect a temporal change of disk composition but requires that both the NC and CC reservoirs co-existed for several Myr. It has further been argued that the formation and co-existence of the CC and NC reservoirs is a natural outcome of the Grand Tack, as follows.

The early formation of the CC and NC reservoirs within ~1 Myr of CAI formation combined with the observation that both reservoirs remained isolated from each other until at least ~3-4 Myr (see sect. 2.4) requires an efficient barrier against radial transport of material. The most obvious candidate is the formation of Jupiter in between the NC and CC reservoirs. The rapid formation of Jupiter's core to ~10-20 M_E impedes radial transport of material, preventing mixing of CC and NC material (Section 3.2.1). Once Jupiter reached ~50 M_E a gap opens in the disk, leading to inwards migration (Section 3.1.4). The inwards-and-outwards motion results in scattering of CC bodies from beyond Jupiter into the inner solar system. The scattering can have occurred no earlier than ~3-4 Myr after CAIs, based on the accretion age of the youngest CC parent body (Kruijer et al. 2017). This scenario is illustrated schematically in Figure 5. So, the Grand Tack can naturally account for both the prolonged spatial separation of the NC and CC reservoirs, and the presence of bodies from both reservoirs in the inner solar system. Moreover, the timescales involved exhibit a strong degree of coherence: the ages of the two flavours imply that gap opening (requiring a massive Jupiter) happened by 3-4 Myr, which is consistent with observed disk dissipation times (Section 2.1). The rapid growth of Mars and dynamical excitation of the asteroid belt are also a natural outcome of this model. While it is too early to conclude that the Grand Tack must have happened, the fact that it can explain geochemical observations which were unknown at the time the hypothesis was being developed is very encouraging.

Likewise, the recent detection of an Oort cloud comet without a water vapor rich tail (a so-called Manx comet; Meech et al. 2016) has been interpreted as an S-type asteroid which was scattered into the outer solar system. If more bodies of this type are found and confirmed to be S-type (as opposed to K-type that are currently impossible to exclude) then this would be a strong argument that some sort of violent dynamical upset – like the Grand Tack – occurred.

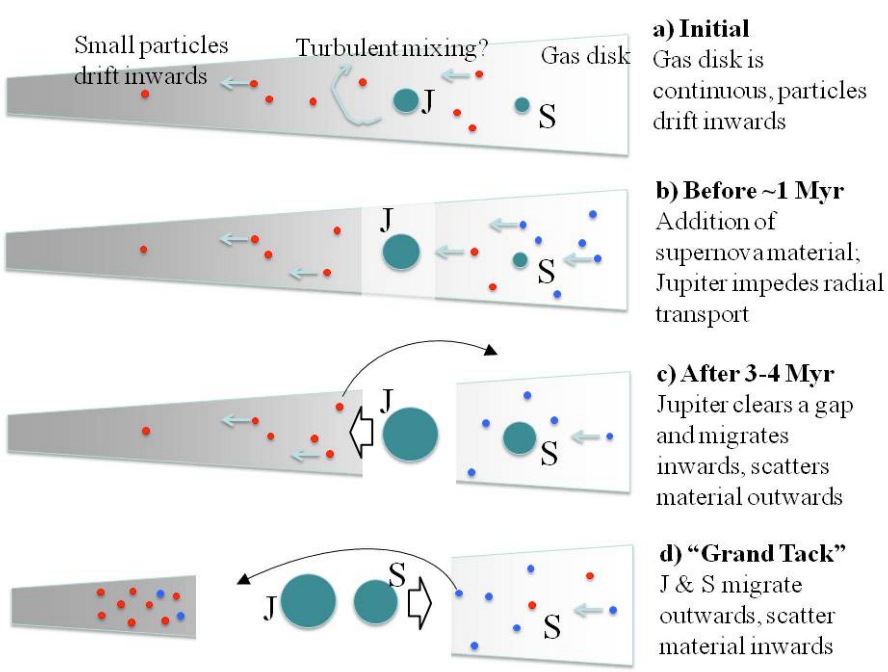

Figure 5. Schematic illustration of emergence of two isotopic flavours, after Kruijer et al (2017). The red and blue dots denote the NC and CC materials. Although this sketch shows addition of

new material beyond Jupiter, the isotopic observations are equally compatible with addition to the inner disk instead.

The Grand Tack, though quite successful, is unlikely to be the only possible explanation. For instance, the isotopic data only require early (<1 Myr after CAIs) isolation of NC and CC reservoirs from each other, and subsequent scattering of CC bodies from beyond Jupiter into the inner solar system, no earlier than 3–4 Myr after CAIs. This scattering need not necessarily be related to the migration of Jupiter and Saturn (as in the Grand Tack model), but could in principle merely be related to the large gravitational influence of a static Jupiter once it reached more than ~50 M_E. In other words, from an isotopic standpoint, Jupiter's migration is not required, as long Jupiter's growth is sufficient to scatter CC bodies into the inner solar system (e.g. Raymond & Izidoro 2017). An early giant planet instability (Section 3.2.5) could result in both inwards scattering of material and a truncated growth of Mars (Clement et al. 2018), but would not explain the dynamical excitation of the asteroid belt.

At present, there seems to be at least one potential objection to the Grand Tack. Because it results in a truncated and dense inner disk, planetary growth is rapid – so rapid, in fact, that the moderate ^{182}W excess measured for the Earth's mantle is hard to explain (Zube et al. 2017). This is because the predicted rapid accretion would naturally lead to large ^{182}W excesses in Earth's mantle. The observed ^{182}W anomaly depends on both accretion timescale and degree of isotopic re-equilibration (Kleine et al. 2009). So one potential solution is to appeal to very effective isotopic re-equilibration throughout the whole accretion process (Zube et al. 2017), but the available fluid dynamical results (Deguen et al. 2014) do not support this argument. It might be that the Earth is simply a statistical outlier, but this is not a very satisfying answer. We regard the fact that the Grand Tack apparently causes the Earth to grow too fast as a significant and currently unsolved problem.

4.2 Pebble Accretion

Although the study of pebble accretion is still in its infancy, it has the great merit of naturally explaining how the gas giants could have formed. There seems little doubt that Jupiter formed within the first 3-4 Myr, and that this was most likely accomplished by core accretion (Section 3.1.3), in which case a ~10 M_E proto-Jupiter was already present. The rapid growth timescales required can be naturally accomplished by pebble accretion.

But the Hf-W evidence shows that the Earth took at least ten times as long to finish its accretion, despite experiencing a higher disk surface density (Section 2.1). Somehow solid-body accretion was rapid in the outer solar system, but protracted in the inner solar system. Whether such different timescales are consistent with pebble accretion remains to be seen. As described in section 3.1.2, this could occur if the pebble and/or planetesimals are naturally smaller interior to the snow line than exterior to it (e.g. Morbidelli et al. 2015, Levison et al. 2015b). However, there is currently no clear evidence of these differences. For instance, although it is often assumed that chondrules represent surviving pebbles, the fact that the size of chondrules in ordinary and carbonaceous chondrites is essentially the same represents a problem (unless the chondrule formation process only occurs after substantial planetary growth has already occurred). Explaining how accretion could have happened so differently in the inner and outer solar systems remains a major challenge. We also note that pure pebble accretion cannot explain the dynamical excitation of the asteroid belt, or the large tilts of some planets (Section 2.5).

Additionally, pebble accretion involves large scale transport of materials in the protoplanetary disk. It has yet to be determined if the compositional differences between different planetary and small bodies is consistent with this type of large-scale movements of material in the protoplanetary disk. Whether inwards drift can be reconciled with the existence of two distinct isotopic “flavours” (Section 2.4), or two spectrally-distinct populations in the asteroid belt, remains to be seen.

4.3 Future Work and Conclusions

Despite the flood of data from exoplanetary systems, studying planet formation in this solar system still has the great advantage of permitting laboratory analysis of sample material. These cosmochemical constraints provide crucial clues, particularly the time it takes terrestrial planets to accrete (Section 2.1). But much more could be done in coupling dynamical simulations to cosmochemistry. For instance, it is currently uncertain whether the rapid accretion implied by the Grand Tack or pebble accretion scenarios is consistent with the Hf-W timing constraints, but this problem has not yet been addressed in any detail. Similarly, the different scenarios imply different degrees of radial mixing, which can be inferred using either isotopes (e.g. Ru-Mo; Section 2.4) or elemental ratios (e.g. K/U; Section 2.3). Again, relatively little work has been done to date to couple this kind of passive tracer into dynamical simulations.

Pebble accretion is a new enough concept that the details are still being worked out. In particular, it is not yet clear how to explain rapid planet growth in the outer solar system simultaneously with sluggish growth closer in (Section 3.1.3). Similarly, so far little attention has been paid to cosmochemical constraints, although Sato et al. (2016) argued that pebble accretion tended to deliver too much water to the Earth, and the same is also likely true of carbon (Levison et al. 2015b). Since pebble accretion by definition happens in the presence of gas, one would imagine that the resulting bodies acquire a substantial inventory of nebular gas and volatiles. Yet at least in the terrestrial planet region, the surviving bodies are quite volatile-depleted (Section 2.3) and show little or no evidence of ancient primitive solar-composition atmospheres. Can these constraints be reconciled with pebble accretion in the inner solar system? Finally, the thermal effects of pebble accretion have not yet been well-studied; rapid accretion can potentially result in significant near-surface heating even in small bodies, though much of the heat may reside in the gas. Whether the internal structures of solar system bodies are compatible with pebble accretion remains to be seen.

Even when samples are not available, spacecraft observations can still be useful. For instance, the Juno and Cassini spacecraft have begun to provide much improved constraints on the interiors and compositions of Jupiter (Wahl et al. 2017) and Saturn, respectively, which will feed into models of how these bodies grew. Given the multiplicity of Neptune-analogues in other solar systems, a similar mission to Uranus or Neptune would seem highly desirable.

Existing constraints on Earth-sized exoplanets are rather scarce, but this picture is likely to improve rapidly and as it does so, the link between system architecture and terrestrial planet growth may become more apparent. One would not expect many extrasolar compositional constraints but, remarkably, we do actually have elemental abundances of solid planetary fragments orbiting other stars - the so-called “polluted white dwarfs” (Jura & Young 2014). These can be used (for instance) to probe whether hypothesized carbon-rich planets are likely to exist, and may in future form a valuable further source of information on planet formation processes.

Despite the successes of both the Grand Tack and pebble accretion scenarios, neither is currently capable of explaining all the available observations, and the compositional/isotopic consequences of these scenarios have not been thoroughly explored. The discrepancy between accretion timescales in the inner and outer solar systems represents an ongoing challenge, and the manner in which the “meter-scale” barrier was overcome is still unclear. In conclusion, there is no shortage of attractive problems to work on.

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